SyRep: Efficient Synthesis and Repair of Fast Re-Route Forwarding Tables for Resilient Networks

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Motivation

- Nowadays communication networks must be highly resilient.
- In modern communication networks with stringent dependability requirements, local fast re-routing (FRR) is essential for a quick response to link failures.
- Configuring FRR for multiple failures is, however, challenging since a router's forwarding table may take into account only the failed links directly incident to it.
- We focus on **repairing** existing routing configurations.

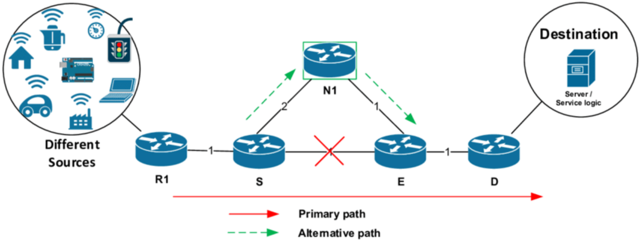


Figure by Papan et al., Sensors'2020.

Motivation

- Nowadays communication networks must be highly resilient.
- In modern communication networks with stringent dependability requirements, local fast re-routing (FRR) is essential for a quick response to link failures.
- Configuring FRR for multiple failures is, however, challenging since a router's forwarding table may take into account only the failed links directly incident to it.
- We focus on **repairing** existing routing configurations using BDDs because:
  - Networks in practice already come with certain mechanisms and forwarding tables
  - This method can be used to efficiently *synthesize* forwarding tables *from scratch*, using a hybrid approach: first, using a fast heuristic that provides close-to-resilient routing tables, and then quickly repair the ill-defined entries using our rigorous BDD approach.

How to react to link failures

Link failures are common in ISP networks as well as data centers.

- A failed link is detected first by the connected routers.
- The routers then usually initiate a reconfiguration of the network.
- Before the process converges, local fast failover protection kicks in.

Local Fast Re-Route (FRR)

If a router is supposed to forward a packet on an interface that is down, it uses instead a preinstalled backup forwarding rule.

Different technologies support FRR.

- **IP fast reroute** uses an alternative ECMP (Equal Cost Multi-Path), loop-free alternative path or multi-hop repair paths.
- In **MPLS networks**, a backup label is pushed on the label stack that goes around the failed link/node (link or facility protection).
- **OpenFlow** uses conditional failover rules with a prioritized list of next-hop interfaces.

Our FRR Model and Perfect Resilience

We study a basic fast re-route protection method where

- packet forwarding is driven by its destination only (no source matching),
- packet headers are not modified, and
- routers store "skipping" forwarding tables: prioritized list of next-hop interfaces per each incoming link and each packet destination.

Perfect Resilience

Our aim is to repair a given network topology's routing configuration (or synthesize it from scratch using a hybrid approach) so that in any failure scenario a packet is delivered to the destination as long as the connectivity between the source and destination is preserved.

Perfect Resilience

Perfectly k-Resilient Routing

A routing table is perfectly k-resilient for a given destination d if

- for any set F of failed links where $|F| \leq k$,
- a packet arriving to any node v is delivered to d as long as v and d are physically connected under the failure scenario F.

A routing is perfectly resilient if this holds for all k.

There are network topologies are not perfectly resilient.

- Feigenbaum et al. [PODC'12] show a network with 12 nodes, 22 edges that is not perfectly 14-resilient.
- Foerster et al. [APOCS'21] show a network with 6 nodes and 9 edges (K3,3) that is not perfectly 3-resilient.
- We prove that every network is perfectly 1-resilient (even if the primary path is an arbitrary chosen shortest path).
- It is an open question whether every network is perfectly 2-resilient.

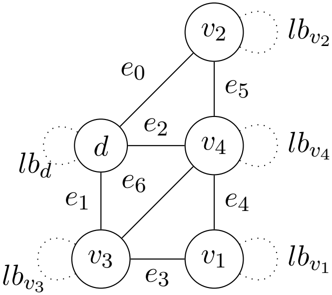
Main Contributions

We design and implement *SyRep*, an efficient and automated approach to repair and synthesize highly dependable fast re-routing tables, providing perfect k-resilience. This is an extension of SyPer that was published on INFOCOM'24.

- We define and implement an automatic method for repairing non-resilient routing tables using BDDs.
- We suggest a fast heuristic algorithm for populating skipping routing tables as well as a method for reducing the size of the synthesized networks by applying structural reduction rules.
- We implement the proposed methodology in a prototype tool SyRep and carry on a comparative experimental evaluation on a large range of the network topologies from the Internet Topology Zoo

Repairing with an Example

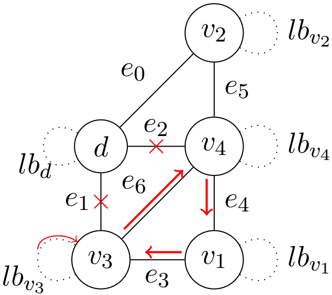
This is a topology and a corresponding forwarding table using skipping routing resilient up to one failure.



in-edge	node	out-edges
lb_{v_1}	v_1	e_3,e_4
e_3	v_1	e_4, e_3
e_4	v_1	e_3,e_4
lb_{v_2}	v_2	e_0, e_5
e_5	v_2	e_0, e_5
lb_{v_3}	v_3	e_1,e_6,e_3
e_3	v_3	e_1,e_6,e_3
e_6	v_3	e_1, e_3, e_6
lb_{v_4}	v_4	e_2,e_4,e_5
e_4	v_4	e_2, e_5, e_6
e_5	v_4	e_2, e_4, e_6
e_6	v_4	e_2,e_4,e_5

Repairing with an Example

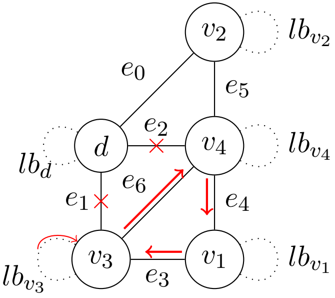
However, this configuration is not resilient to every two link failures. Our method investigates all possible scenarios and marks the used entries.



in-edge	node	out-edges
lb_{v_1}	v_1	e_3, e_4
e_3	v_1	e_4, e_3
e_4	v_1	e_3, e_4
lb_{v_2}	v_2	e_0, e_5
e_5	v_2	e_0, e_5
lb_{v_3}	v_3	e_1, e_6, e_3
e_3	v_3	e_1, e_6, e_3
e_6	v_3	e_1, e_3, e_6
lb_{v_4}	v_4	e_2, e_4, e_5
e_4	v_4	e_2, e_5, e_6
e_5	v_4	e_2, e_4, e_6
e_6	v_4	e_2, e_4, e_5

Repairing with an Example

Using BDDs we try to replace the marked entries with new ones. Indeed, if we erase e_4 from the last row (i.e. replaced with e_5), the configuration becomes perfectly 2-resilient.



in-edge	node	out-edges
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e_3	v_1	e_4, e_3
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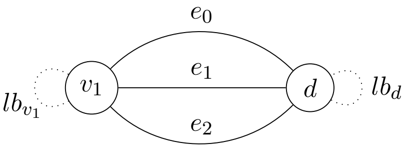
e_5	v_2	e_0, e_5
lb_{v_3}	v_3	e_1, e_6, e_3
e_3	v_3	e_1, e_6, e_3
e_6	v_3	e_1, e_3, e_6
lb_{v_4}	v_4	e_2, e_4, e_5
e_4	v_4	e_2, e_5, e_6
e_5	v_4	e_2, e_4, e_6
e_6	v_4	$e_2, \cancel{e_4}, e_5$

How does a BDD look like? (an even smaller example)

Idea

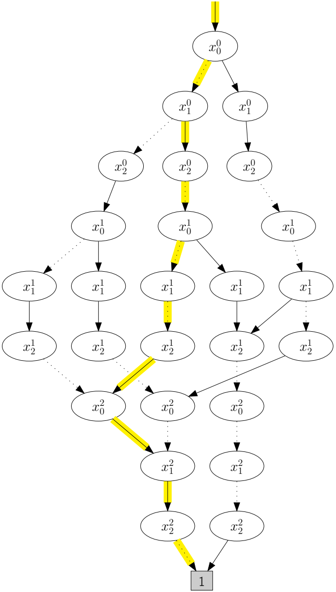
Represent routing tables as Boolean functions and store them in the compact data structure Binary Decision Diagrams (BDD).



Edges are ordered as: lb_d, lb_{v_1}, e_0 , e_1 , e_2

Highlighted path encodes the priority list:

$$x_2^0 x_1^0 x_0^0 = 010 \rightarrow e_0$$
$$x_2^1 x_1^1 x_0^1 = 100 \rightarrow e_2$$
$$x_2^2 x_1^2 x_0^2 = 011 \rightarrow e_1$$



BDD formulation

Encoding of next-hop

$$\mathcal{T}(\overline{\mathbf{e}}_{in}, \overline{\mathbf{v}}, \overline{\mathbf{e}}_{out}, \overline{\mathbf{v}}', \overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k, [\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e} : {}^{e\in E}_{v\in r(e)}]) =$$

$$state(\overline{\mathbf{v}}, \overline{\mathbf{e}}_{in}) \wedge state(\overline{\mathbf{v}}, \overline{\mathbf{e}}_{out}) \wedge state(\overline{\mathbf{v}}', \overline{\mathbf{e}}_{out}) \wedge$$

$$\overline{\mathbf{e}}_{out} \notin \{\overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k\} \wedge$$

$$\bigwedge_{e\in E \wedge v\in r(e)} \mathcal{V}_{v,e}(\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e}) \wedge$$

$$\bigwedge_{e\in E} \bigwedge_{v\in r(e)} \Big(\overline{\mathbf{e}}_{in}(e) \wedge \overline{\mathbf{v}}(v) \implies \overline{\mathbf{e}}_{out} \in \{\overline{\mathbf{e}}^0_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e}\}\Big) \wedge$$

$$\bigwedge_{i\in 0,..,k} \bigwedge_{e\in E} \bigwedge_{v\in r(e)} \Big(\overline{\mathbf{e}}_{in}(e) \wedge \overline{\mathbf{v}}(v) \wedge \overline{\mathbf{e}}^i_{v,e} \notin \{\overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k\} \wedge$$

$$\{\overline{\mathbf{e}}^0_{v,e}, ..., \overline{\mathbf{e}}^{i-1}_{v,e}\} \subseteq \{\overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k\} \implies \overline{\mathbf{e}}_{out} = \overline{\mathbf{e}}^i_{v,e}\Big)$$

Encoding of packet delivery

$$\mathcal{D}_{n+1}(\overline{\mathbf{e}}_{in}, \overline{\mathbf{v}}, \overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k, [\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e} : {}^{e\in E}_{v\in r(e)}]) =$$

$$\mathcal{D}_n(\overline{\mathbf{e}}_{in}, \overline{\mathbf{v}}, \overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k, [\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e} : {}^{e\in E}_{v\in r(e)}]) \vee$$

$$\Big(\exists \overline{\mathbf{v}}', \overline{\mathbf{e}}_{out} :$$

$$\mathcal{T}(\overline{\mathbf{e}}_{in}, \overline{\mathbf{v}}, \overline{\mathbf{e}}_{out}, \overline{\mathbf{v}}', \overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k, [\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e} : {}^{e\in E}_{v\in r(e)}])$$

$$\wedge \mathcal{D}_n(\overline{\mathbf{e}}_{out}, \overline{\mathbf{v}}', \overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k, [\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e} : {}^{e\in E}_{v\in r(e)}])\Big)$$

Encoding of all perfectly k-resilient routings

$$\mathcal{P}([\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e} : {}^{e\in E}_{v\in r(e)}]) =$$

$$\forall \overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k : \forall (\overline{\mathbf{e}}_s, \overline{\mathbf{s}}) :$$

$$\Gamma(s(\overline{\mathbf{s}}), f_1(\overline{\mathbf{f}}_1), ..., f_k(\overline{\mathbf{f}}_k), d) \implies$$

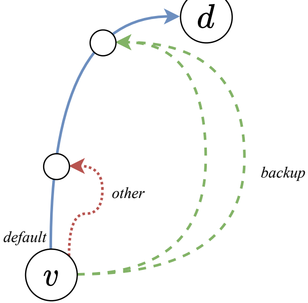
$$D(\overline{\mathbf{e}}_s, \overline{\mathbf{s}}, \overline{\mathbf{f}}_1, ..., \overline{\mathbf{f}}_k, [\overline{\mathbf{e}}^0_{v,e}, \overline{\mathbf{e}}^1_{v,e}, ..., \overline{\mathbf{e}}^k_{v,e} : {}^{e\in E}_{v\in r(e)}])$$

Fast generation of routing tables: Heuristic Routing Generation

Our heuristic generates close-to-resilient routings by extending the algorithm described in the SyPer paper. Formally, we define a skipping routing R such that for every edge $e \in E$ and every node $v \in V \setminus \{d\}$

- if $e \neq e_v$ then $R(e, v) := (e_v, e_1, e_2, \ldots, e_\ell, e'_1, e'_2, \ldots, e'_m, e)$
- otherwise $R(e_v, v) := (e_1, e_2, \ldots, e_\ell, e'_1, e'_2, \ldots, e'_m, e_v)$

where $e_1, e_2, \ldots, e_\ell$ are all backup edges for v (in an arbitrary order) and $e'_1, e'_2, \ldots, e'_m$ are all the remaining edges (different from e_v and the backup edges) connected to v.



Fast generation of routing tables: Structural Reduction Methods

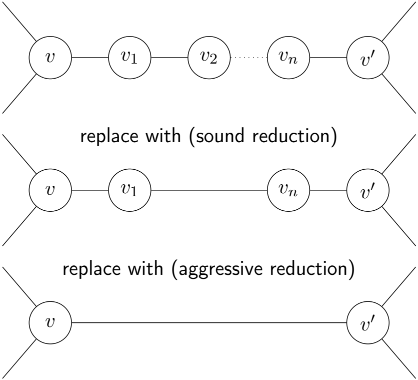
Reducing the size of the network can speed up the synthesis of resilient routing configurations. We present two reduction rules with different guarantees.

Sound chain-reduction:

- provably correct
- limited size reduction

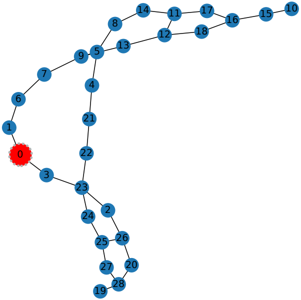
Aggressive chain-reduction:

- much more size reduction (super-set of sound version)
- the expanded version is not always resilient (but we can try to repair it)

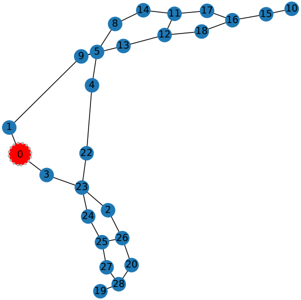


Structural Reduction Example

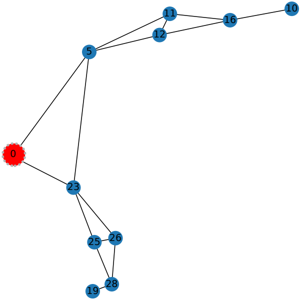
Effect of the two structural reduction rules on the *BizNet* topology where node 0 is the destination node.



Original (29 nodes)

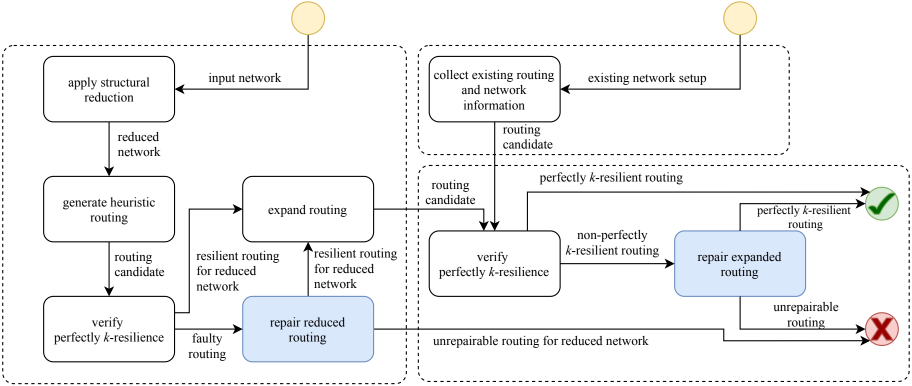


After sound reduction (26 nodes)



After aggressive reduction (11 nodes)

Combined framework with modular architecture

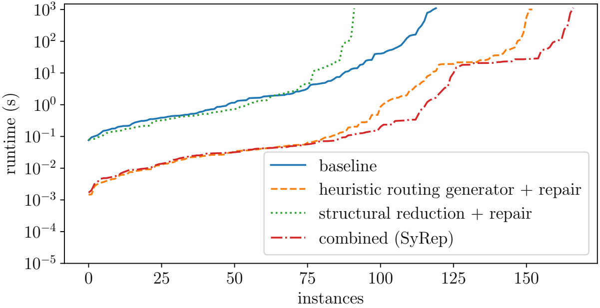


Implementation and experiments

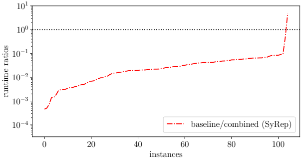
- SyRep implements in Python and uses the CUDD BDD library.
- Open-source tool, reproducibility package available.
- Evaluated on Topology Zoo benchmark of ISP network topologies (243 connected networks with up to 700 nodes).
- We try to find 2- and 3-resilient routings using BDDs with 20 minutes timeout and 128 GB memory limit.
- (Our baseline is the original SyPer tool.)

Topology Zoo benchmark $k = 2$

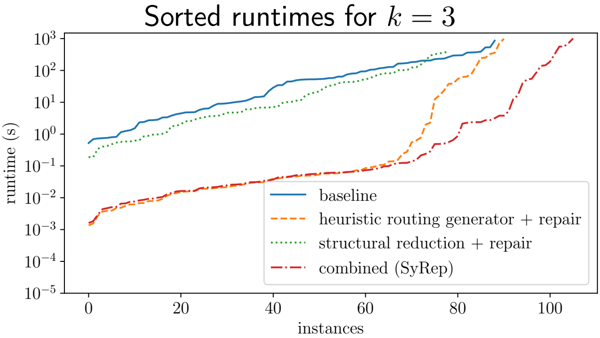
Sorted runtimes for $k = 2$

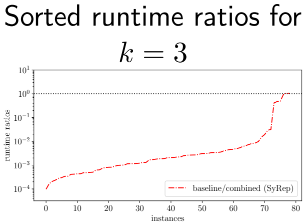


Sorted runtime ratios for $k = 2$

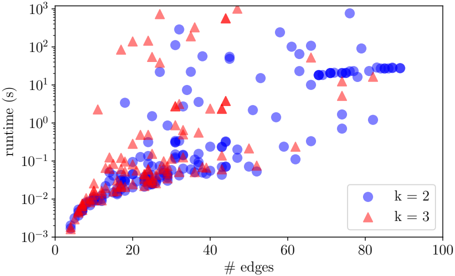


Topology Zoo benchmark $k = 3$

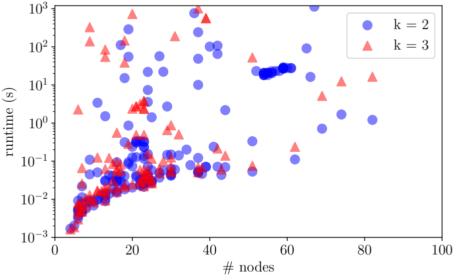




Network size vs. runtime



Network size (**number of edges**) vs. runtime



Network size (**number of nodes**) vs. runtime

Related Work: Resilient networking

- M. Chiesa, A. Kamisiński, J. Rak, G. Rétvári, and S. Schmid, "A survey of fast recovery mechanisms in the data plane," TechRxiv, May 2020.
- K.-T. Foerster, A. Kamisinski, Y.-A. Pignolet, S. Schmid, and G. Trédan, "Grafting arborescences for extra resilience of fast rerouting schemes," in INFOCOM 2021
  - this algorithm does not provide any formal guarantees
- The problem for graphs with certain properties is also widely studied.
- Fast re-routing solutions have also been studied for networks which support dynamic packet headers modifications and/or source matching.

Related Work: Synthesis and Formal methods

- Many interesting synthesis and formal methods approaches have been presented for other aspects of networking.
- *SyNET (CAV'17)* synthesizes correct network configurations for routing protocols such as BGP and OSPF
- *AalWines (CoNEXT'20)* provides an automated what-if verification of the policy-compliance of routes under multiple failures in MPLS networks.
- There are also tools to automatically and correctly update network configurations, such as *NetComplete (NSDI'18)* and *AllSynth (TASE'22)*, which ensure policy compliance.
  - AllSynth also leverages BDDs.

Conclusion and Open Questions

Contributions

- Quickly repairing existing forwarding tables using BDDs.
- Investigating heuristics to speed up the synthesis of routing configurations.
- Efficiently synthesize forwarding tables from scratch, using a hybrid approach.

Open questions:

- There exist other heuristic approaches for routing synthesis like e.g. Grafting. Are there heuristics with better/worse repairability?
- Can we use repairing to handle dynamically changing networks?
- As another future work, it will be interesting to extend our tool to provide additional desirable properties beyond connectivity, e.g., accounting for link utilization or congestion along backup paths.